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13. SUPPLEMENTARY NOTES Presented at Mirror Technology Days, Boulder, Colorado, USA, 7-9 June 2010.					
14. ABSTRACT The surface figure error on mirrors can be divided into low, mid, and high spatial frequency errors. Conventional optical aberrations are represented by the low frequency errors. Finish (also gloss or roughness) are described by the high frequency errors. Mid frequency errors are typically the cause of small angle scattering. A process called VIBE, which uses a vibrating lap, was applied to flat borosilicate glass surfaces for up to 60 seconds. Only nanometers of material were removed. Tens of compliant polishing pads were evaluated with the technique. The power spectral density was used to evaluate frequency content. Initial results indicate that VIBE finishing can reduce the mid-frequency errors on flats.					
15. SUBJECT TERMS Figure, error, surface accuracy, mirrors, lap, vibrating lap, power spectral density, mid-frequency, finish					
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# Eliminating Mid-Spatial Frequency (MSF) Errors with VIBE Finishing

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Order/Contract Number: NNX10CF20P

June 8, 2010

NASA Mirror Technology Days



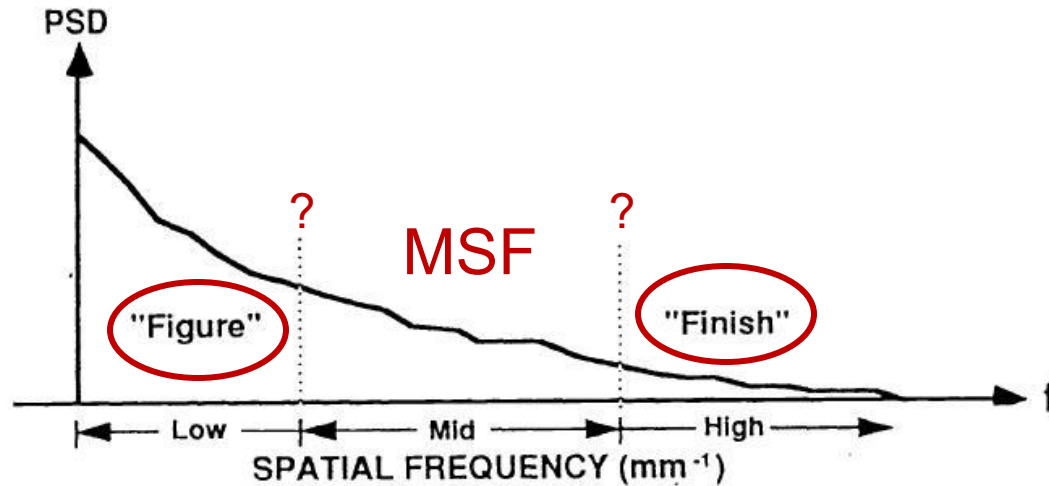
# Outline

- Introduction
  - Mid-Spatial Frequency (MSF) Errors
  - VIBE Technology
- Characterization of MSF Errors
- MSF Error Removal with VIBE

# Outline

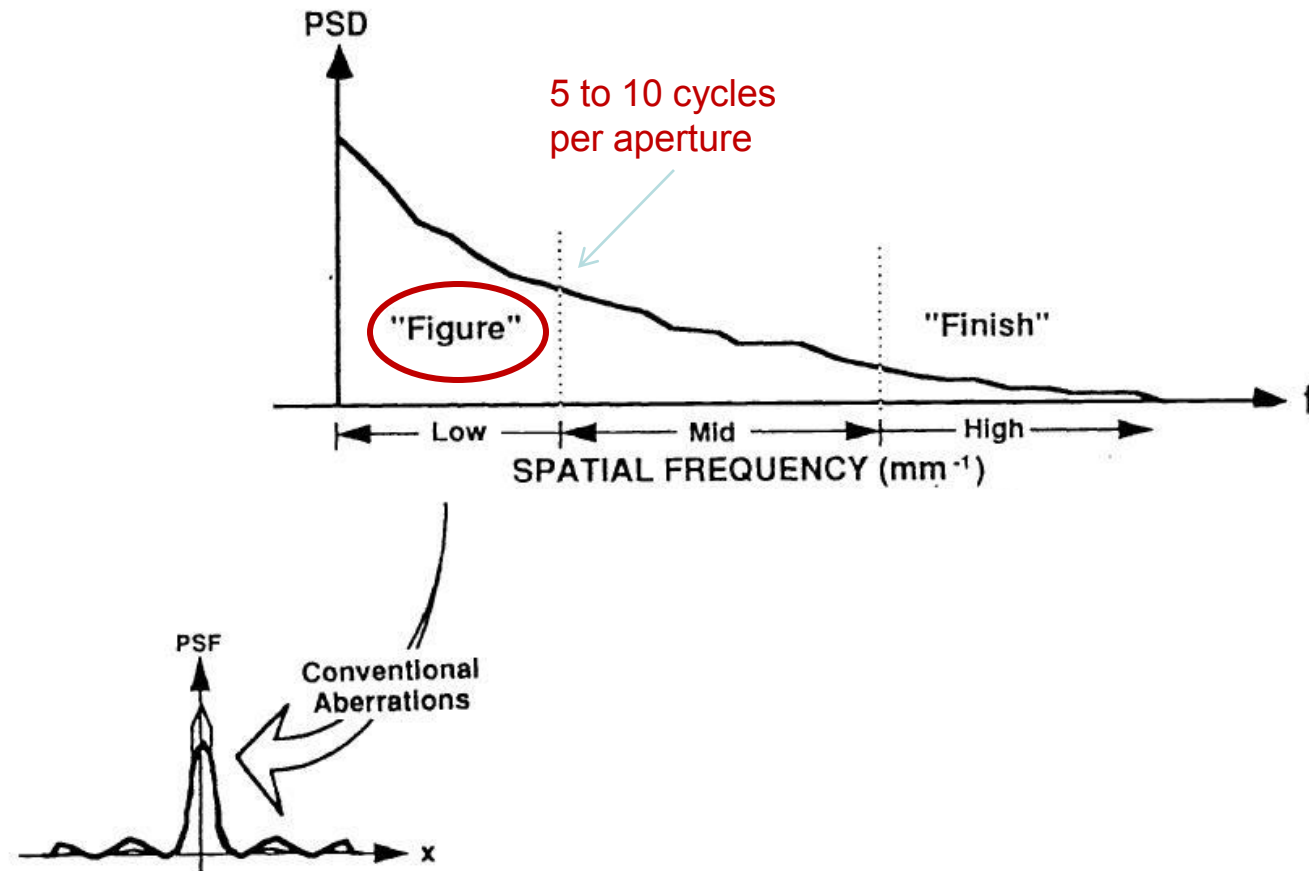
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# What is —mid-spatial frequency”?



J.E. Harvey and A. Kotha, —Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

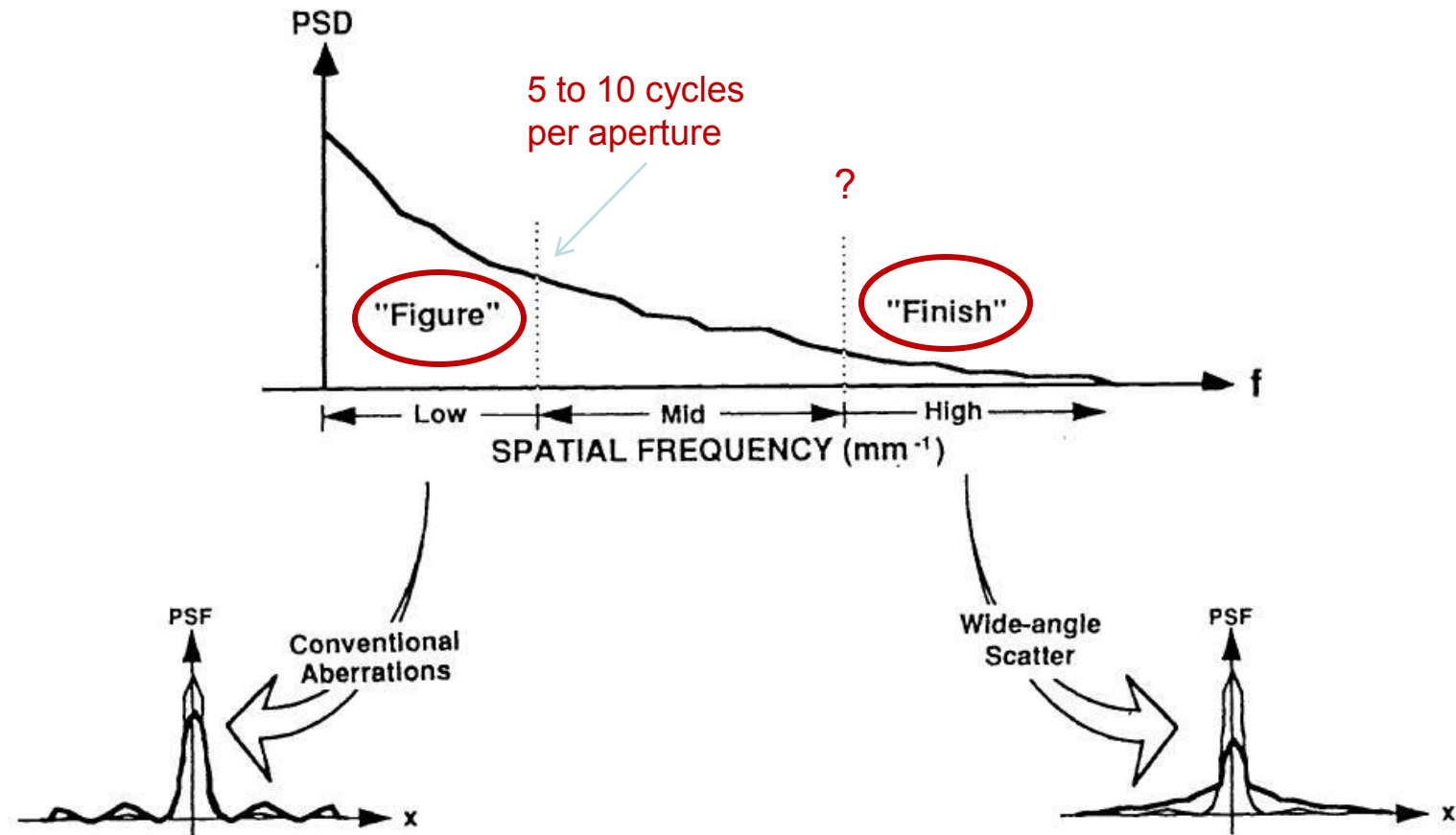
Figure is the range of spatial frequencies addressable with a simple Zernike expansion



J.E. Harvey and A. Kotha, —Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

D. Aikens, J. E. DeGroote, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).

Finish (a.k.a. “loss” or “roughness”) is typically less critical as it results in total transmission loss

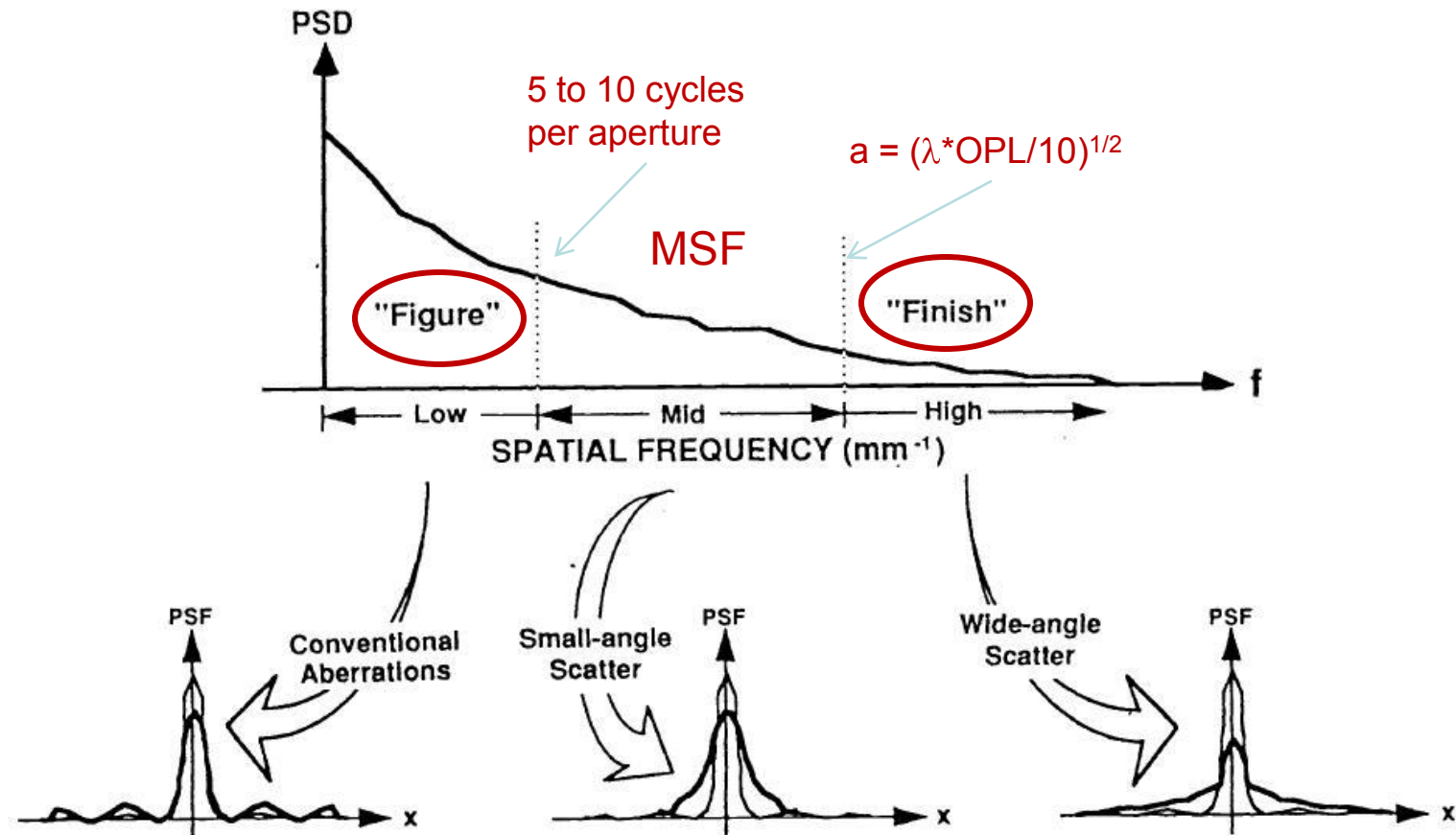


J.E. Harvey and A. Kotha, “Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

D. Aikens, J. E. DeGroot, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).



# Mid-Spatial Frequency bandwidth limits help to define the MSF itself



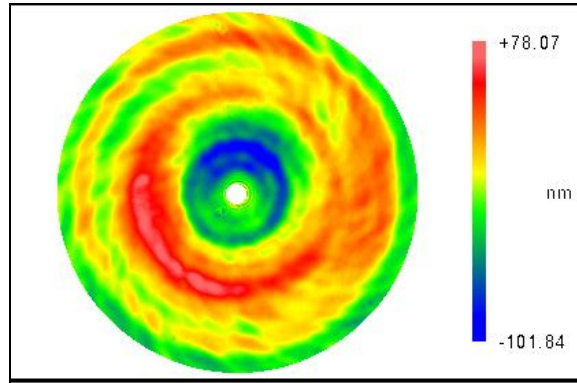
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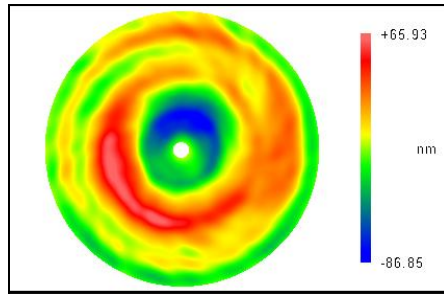
# Example: Spoke and Spiral Errors

**PV: 179.9nm**  
**RMS: 28.6nm**



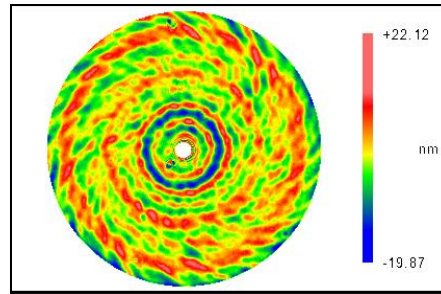
Unfiltered data

**PV: 152.8nm**  
**RMS: 26.3nm**



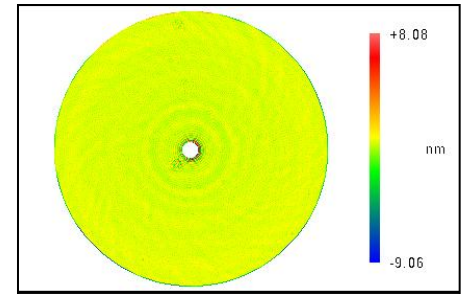
Low spatial  
frequency

**PV: 41.9nm**  
**RMS: 4.8nm**



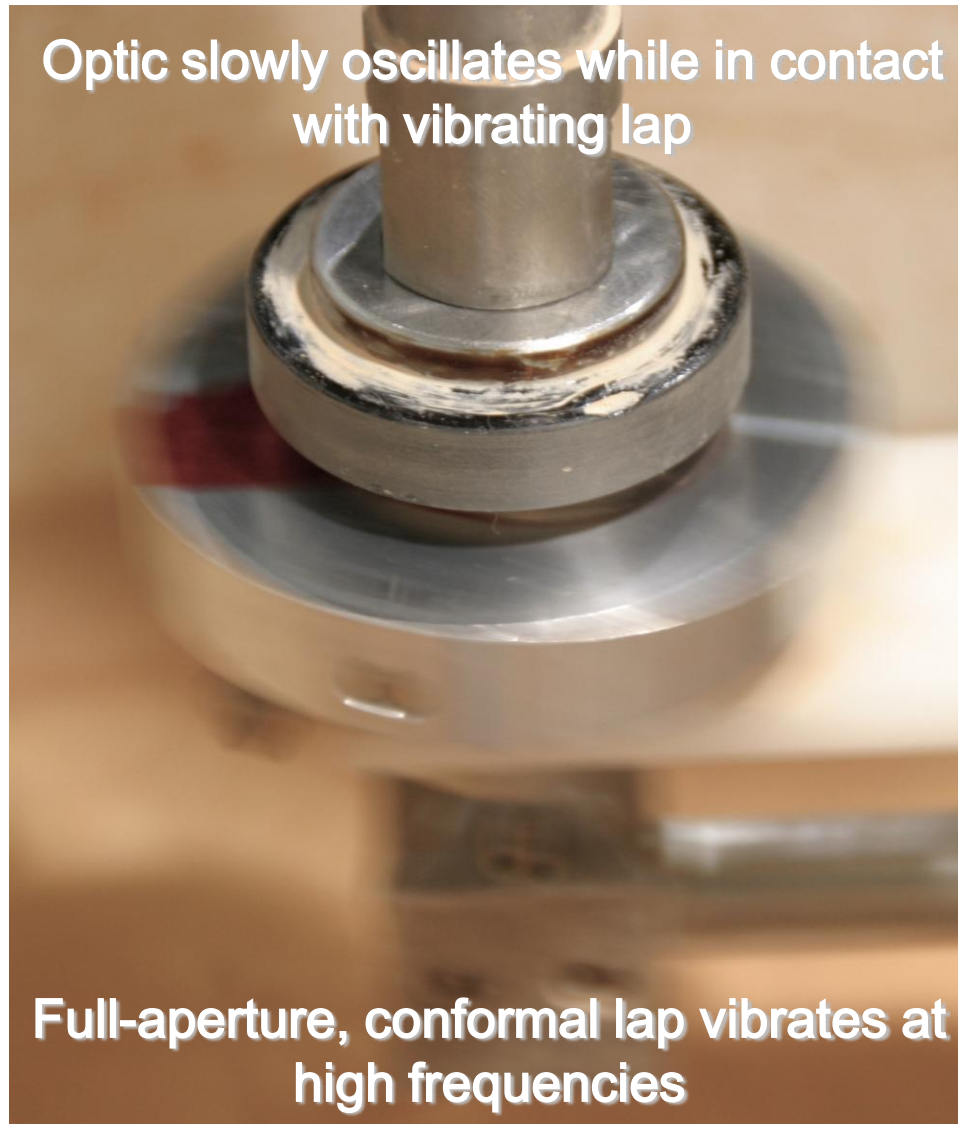
Mid-spatial  
frequency

**PV: 17.1nm**  
**RMS: 0.6nm**



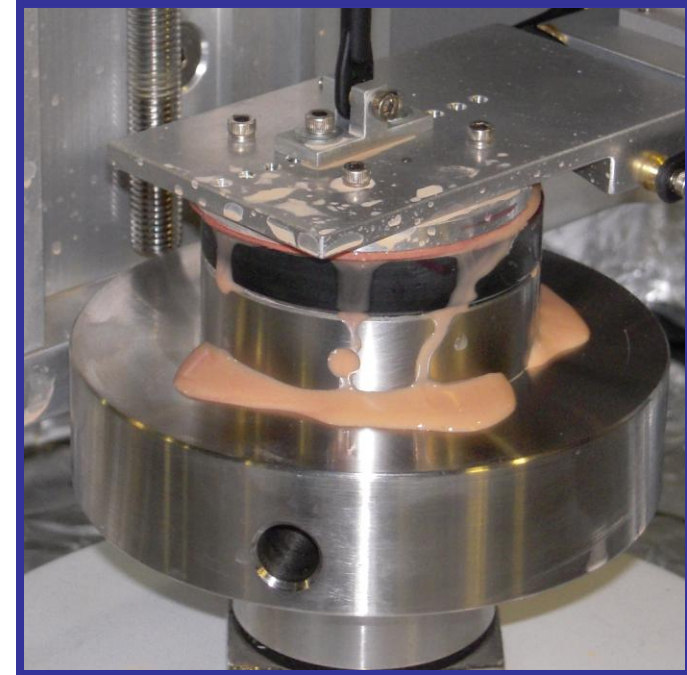
High spatial  
frequency

# VIBE Process is a high-pressure, high-speed, full aperture polishing process

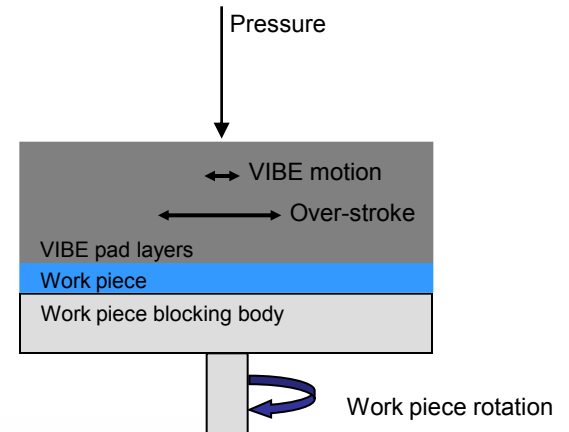


# VIBE testing station provides platform for pad/slurry experimentation

- VIBE removal rate studies
- In-process testing of polishing pads
- Variable pressure and speed



# VIBE linear motion with over-stroke



**Vibe linear motion with over-stroke**



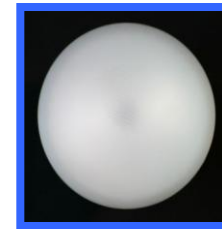
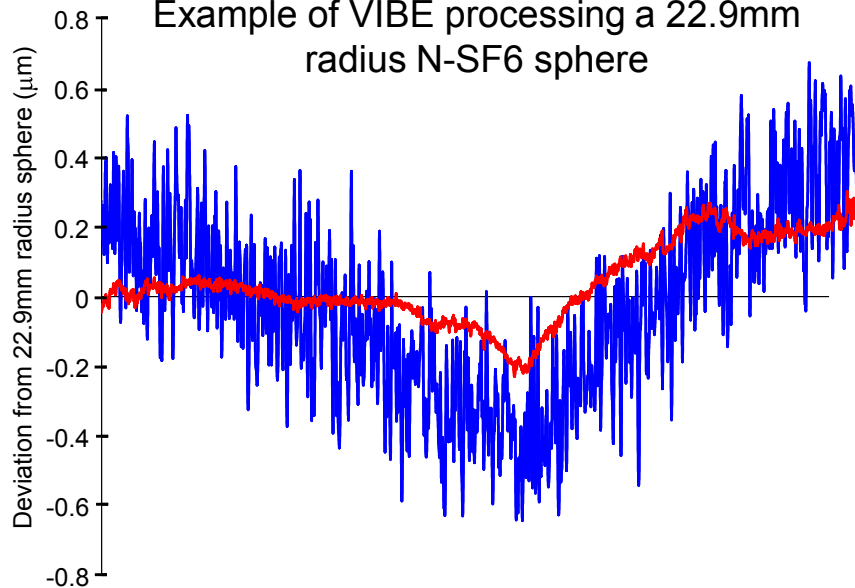
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Animation speed and motion has been exaggerated for viewing purposes



# VIBE originally intended for pre-polishing glass spheres and aspheres

Example of VIBE processing a 22.9mm radius N-SF6 sphere

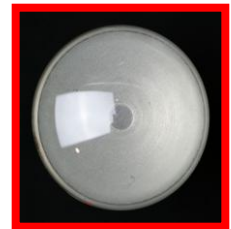


Initial 9T alumina ground surface

Areal surface roughness

P-V: 8517.6nm

RMS: 756.1nm



After 10 minutes of VIBE polishing

Areal surface roughness

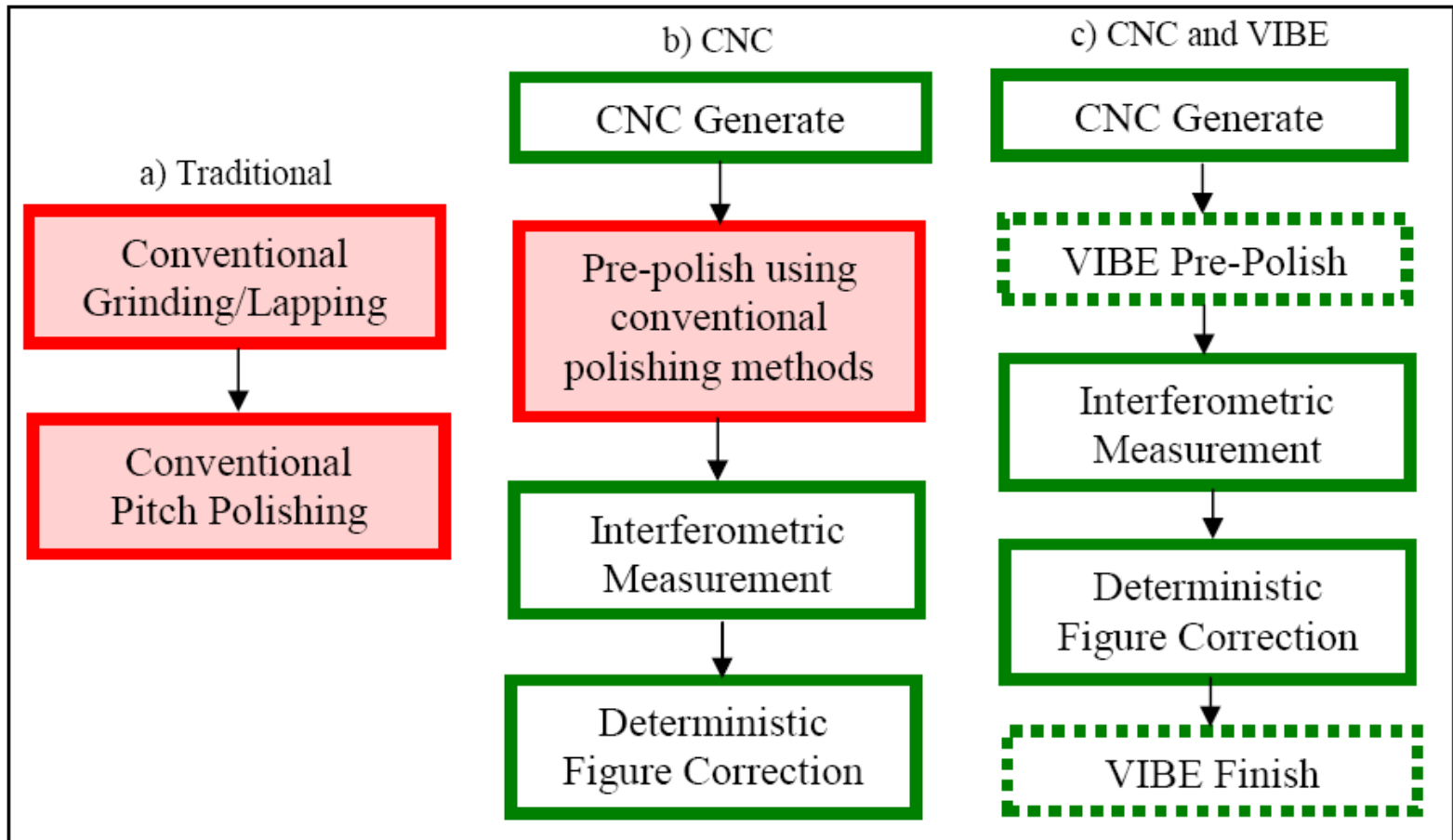
P-V: 12.3nm

RMS: 0.7nm

In just 10 minutes...

- Remove 10μm
- Improve surface figure
- Improve surface roughness by 100x

# The role of VIBE in modern optical manufacturing processes





# Outline

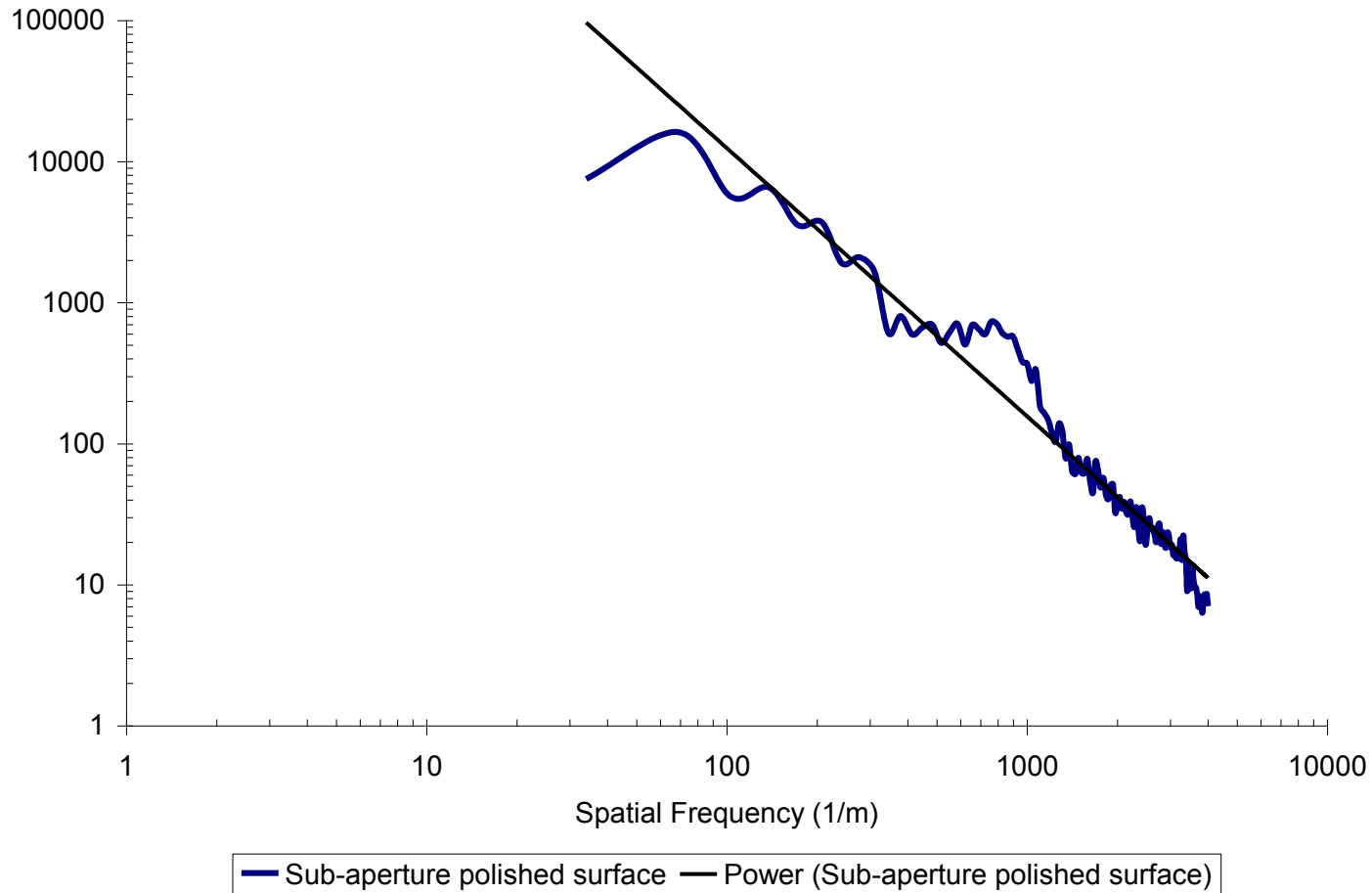
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# Characterizing MSF Errors

- Implemented three different ways to visualize MSF errors
  - Power Spectral Density
  - Zernike Residual RMS
  - Slope Error

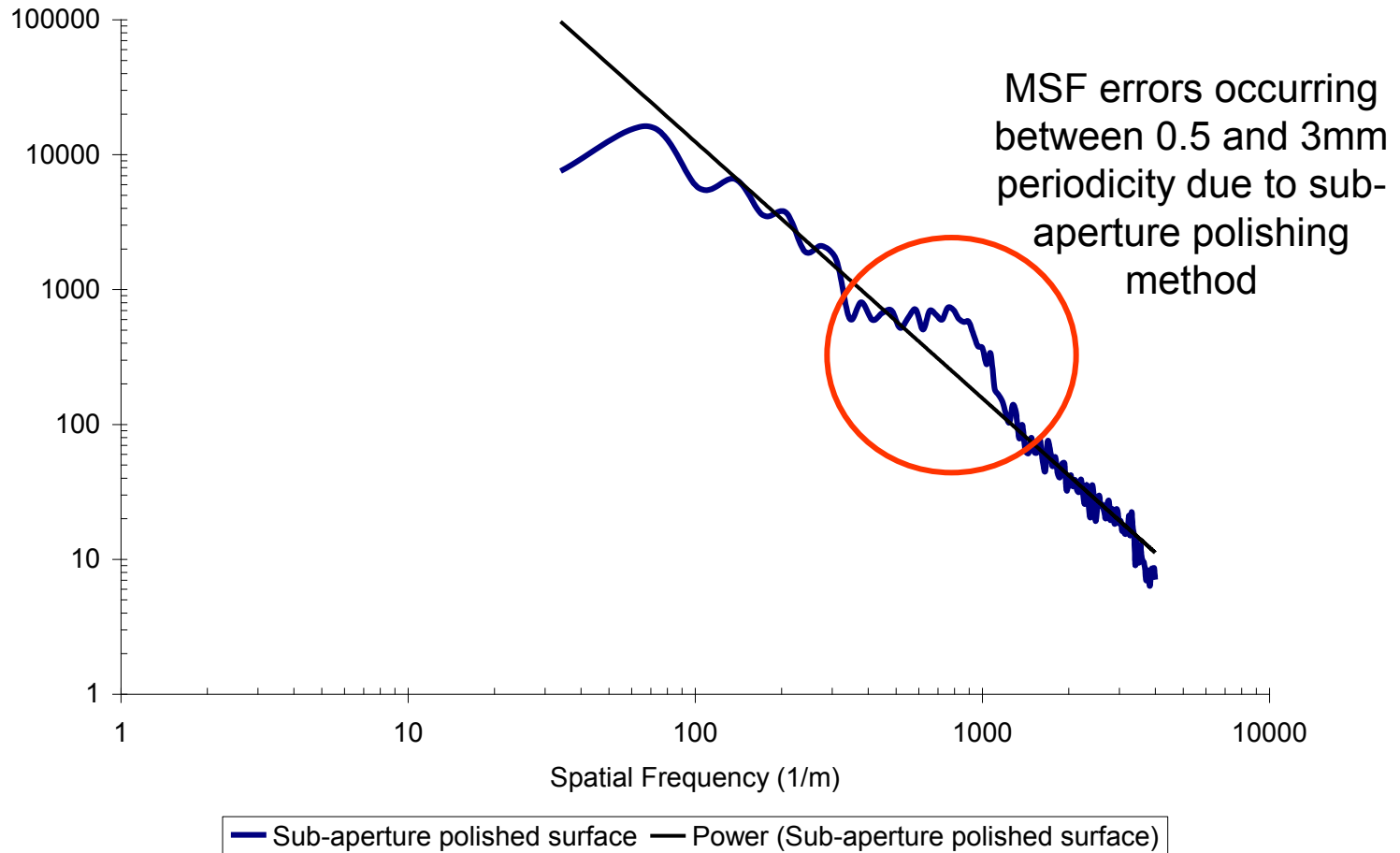
# Power Spectral Density (PSD)

- Deviation from straight line



# Power Spectral Density (PSD)

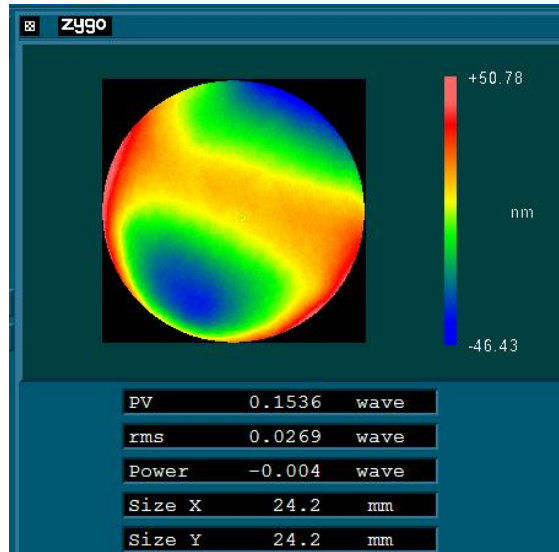
- Deviation from straight line



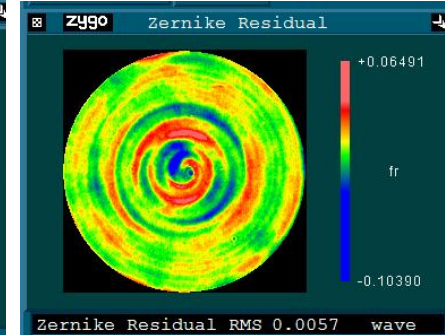
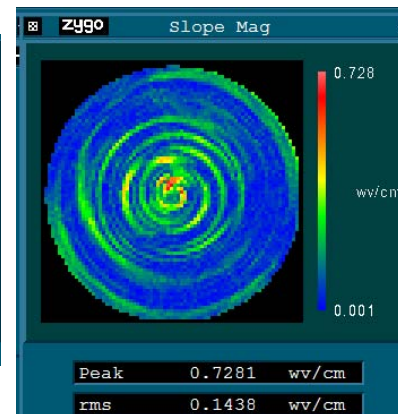
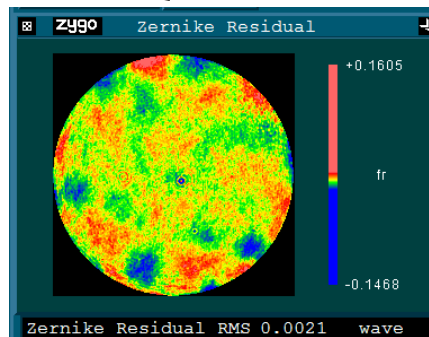
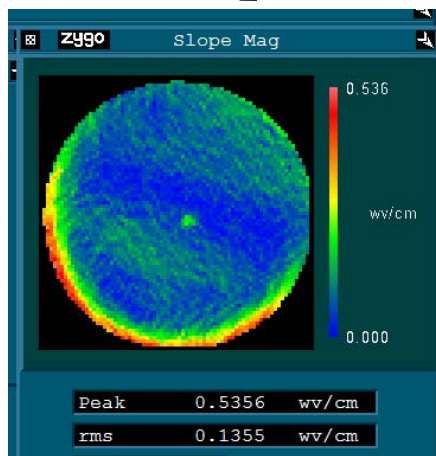
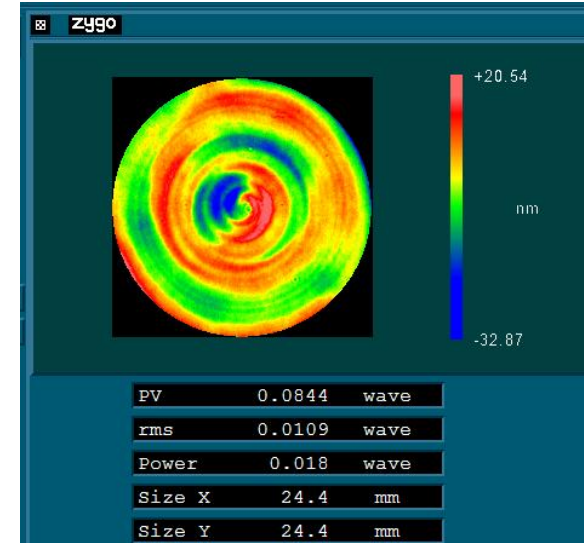
# Residual RMS and Slope data

## Implemented for initial inspection

Pitch Polished Surface



Sub-aperture Rotationally Polished Surface



# Outline

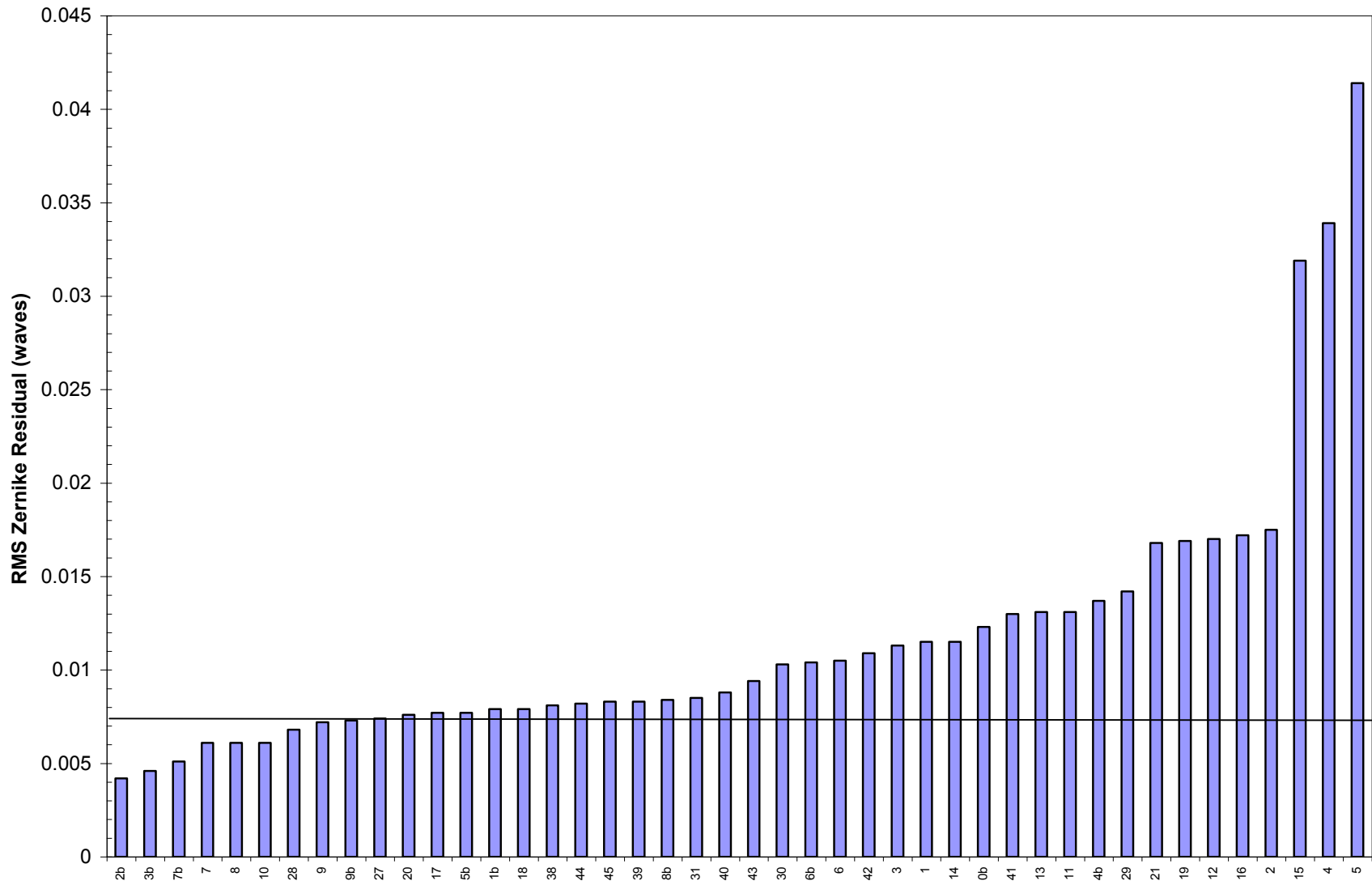
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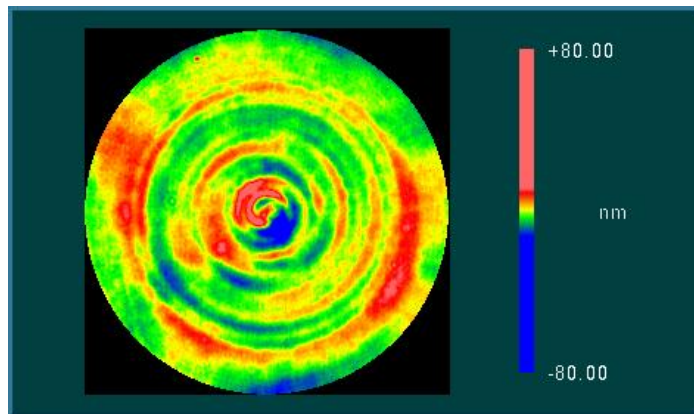
# Implementing VIBE to remove MSF errors

- Currently 4 months into Phase I
- Examining different compliant mediums to determine optimum polishing pad composition
  - Material
    - Borosilicate glass
    - Initial surface – sub-aperture figure correction of plano surface
- Only remove nanometers of material
  - VIBE finishing step completed in less than 60 seconds

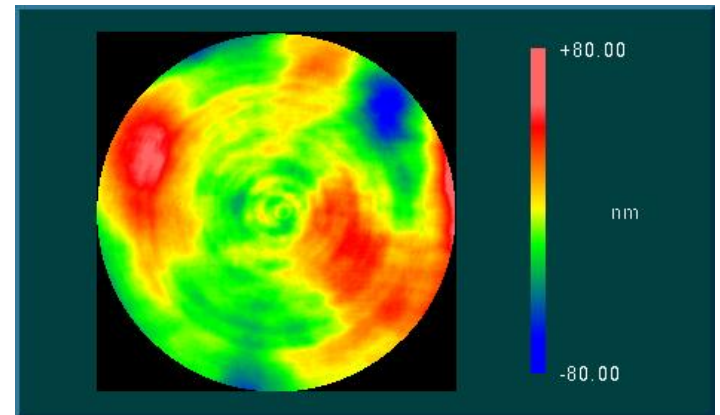
We have examined many different types of compliant polishing pads with mixed results



# We have been able to reduce the appearance of MSF errors with VIBE

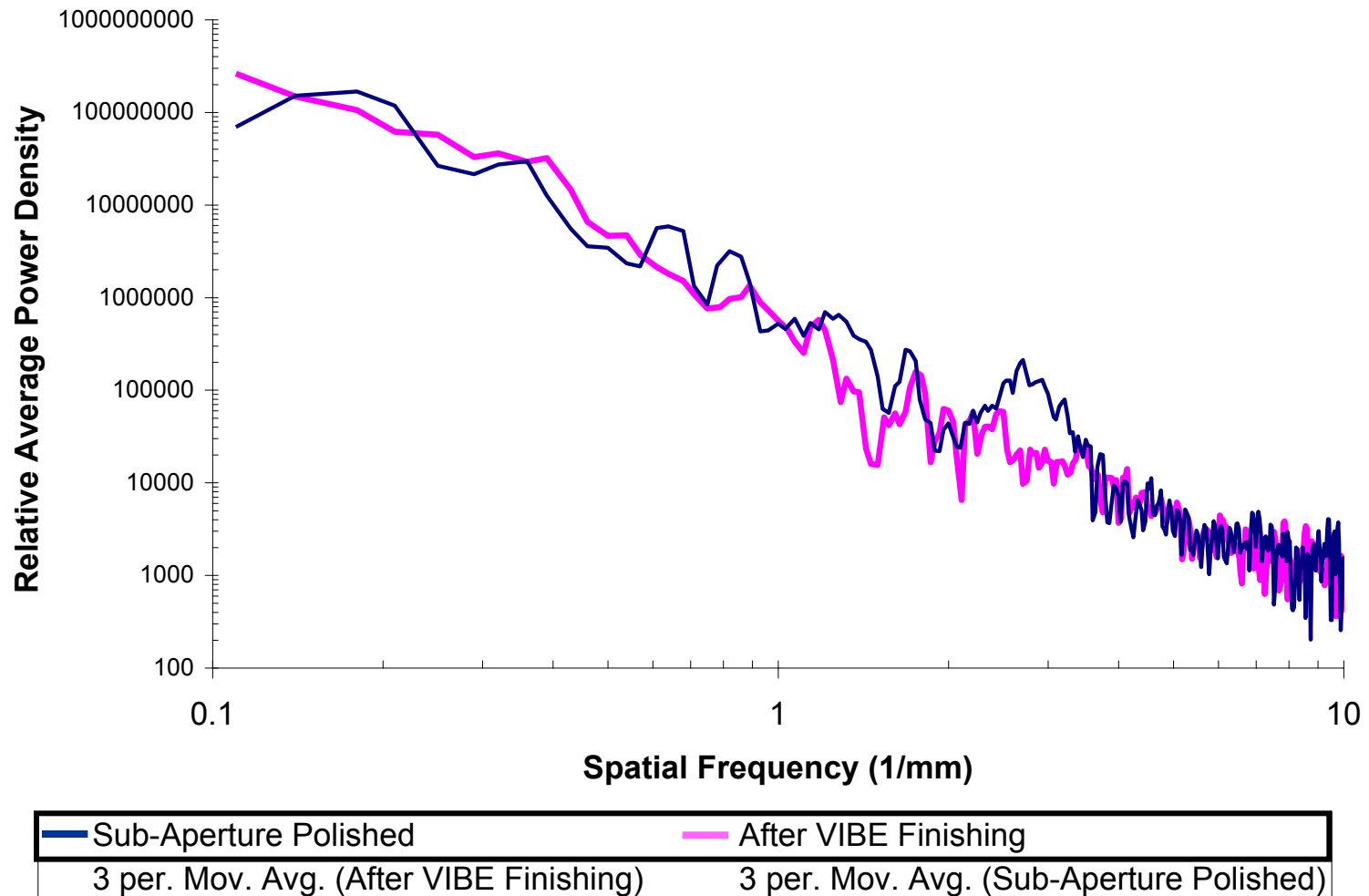


Initial Sub-Aperture Polished Surface



Surface After 60-second VIBE Finishing

# PSD data shows that VIBE finishing can reduce MSF errors



# Conclusions and Future Work

- VIBE finishing can reduce the appearance of MSF errors on flat rotationally polished surfaces
- Continued work on eliminating MSF errors
- Future work: extend technology to spheres, cylinders, aspheres and conformal optics

# Acknowledgements

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  - Phil Stahl (NASA)
  - John Lehan (Univ. of Maryland)
  - Peter Blake (NASA)
- NASA SBIR program for funding this work



# Eliminating Mid-Spatial Frequency Errors with VIBE

*Optimax Systems, Inc.  
Ontario, NY*

## INNOVATION

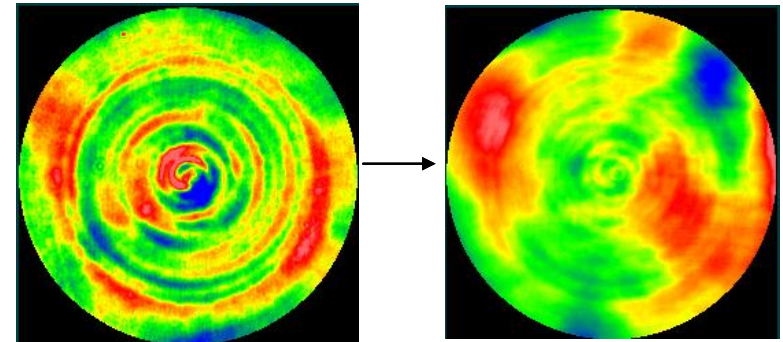
The Optimax VIBE process is a full-aperture, conformal polishing process incorporating high frequency and random motion to *eliminate mid-spatial frequency (MSF) errors* created by deterministic polishing in a VIBE finishing step while maintaining low spatial frequency form accuracy.

## ACCOMPLISHMENTS

- ◆ Currently in Phase I SBIR – Development Stage
- ◆ VIBE finishing has been shown to reduce the severity of MSF errors
- ◆ We have incorporated repeatable interferometric methods to characterize MSF errors

## COMMERCIALIZATION

- ◆ Optimax VIBE™ Technology
- ◆ U.S Patent Number 6942554 B1
- ◆ Primary target applications: Optical imaging systems where small angle scatter would reduce performance quality
- ◆ Optimax currently provides high precision optics to the aerospace, defense, medical and imaging markets, VIBE technology will enhance our capabilities
- ◆ Current customers are designing all spherical optical systems due to Asphere manufacturing limitations (MSF errors)
- ◆ MSF errors are formed during deterministic sub-aperture polishing processes. MSF errors cause small angle scatter and flare in optical systems.
  - ◆ VIBE Finishing will eliminate these undesirable MSF errors



Initial Sub-Aperture  
Polished Surface

Surface After 60-  
second VIBE  
Finishing

*Sub-aperture polished surface before and after VIBE finishing*

## GOVERNMENT/SCIENCE APPLICATIONS

### NASA:

- ◆ X-Ray Telescopes:
  - ◆ IXO – slumping mandrels, produce surfaces less than 1.4nm rms between 2-20mm spatial frequency range.
- ◆ Exo-Planet Imaging Systems:
  - ◆ Minimize scatter on primary and secondary mirrors, specifically less than 1nm rms in 4-50 cycles/aperture range

### Non-NASA:

- ◆ High Energy Laser Systems, EUV Optics (Lithography), Imaging Systems and X-Ray Synchrotron Optics